Laser Heater for the Multi-Stage Compressor Superconducting FEL Driver of FLASH2020+.

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LEDS23 / Frascati, IT / 2023-10-05

for my colleagues: **Ch.Gerth**, D.Samoilenko, L.Schaper, S.Schreiber, M.Vogt, C.Mai
and many other contributors to the Laser Heater Project at FLASH2020+

HELMHOLTZ

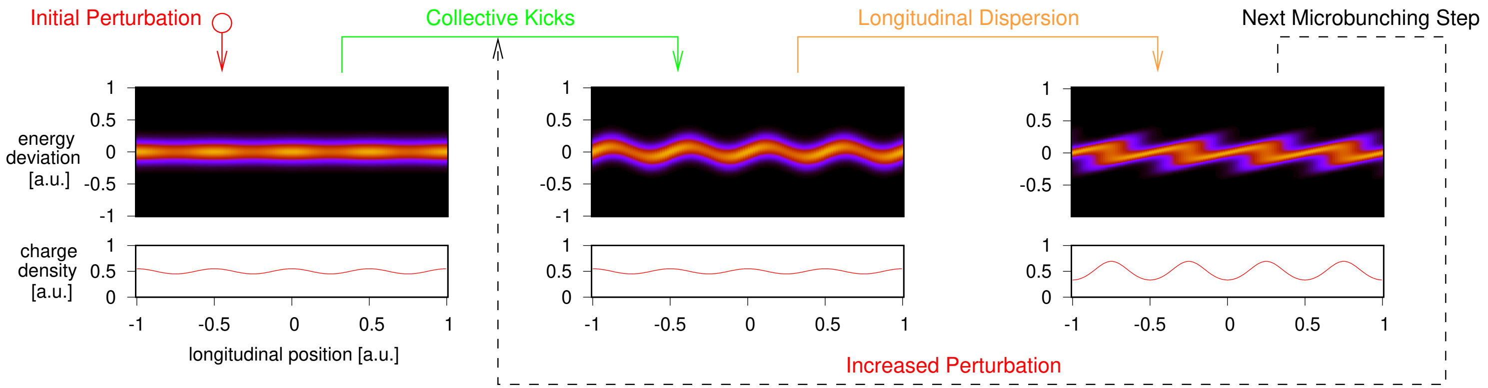
v1

DESY.

Outline.

- FLASH2020+ Laser Heater
  →Layout
  →Commissioning
- SASE Studies
- Microbunching Studies
  →Radon-Transform Image Analysis
- FLARE Project (brief introduction)

Motivation: Microbunching Instability Mechanism.



- Mechanism:
  →Charge-density perturbations cause collective kicks
  →collective kicks induce energy modulations
  →Energy modulations are sheared by longitudinal dispersion
  ↪potential increase of charge-density perturbations
- Fundamental process, occurs also in: FEL process, Klystron, etc.

Possible Counter Measure: Add Energy Spread.

TTF (2003)

TESLA-FEL-2003-02

May 2003

Longitudinal Space Charge Driven Microbunching Instability in TTF2 linac

E.L. Saldin [a], E.A. Schneidmiller [a], M.V. Yurkov [b]

Abstract

In this paper we study a possible microbunching instability (amplification of parasitic density modulations) in the TESLA Test Facility (Phase 2) linac. A longitudinal space charge field is found to be the main effect driving the instability. Analytical estimates show that initial perturbations of beam current in the range 0.5-1 mm will be amplified by a factor of a few hundred after the beam passed two bunch compressors. A method to suppress the instability is discussed.

[...]

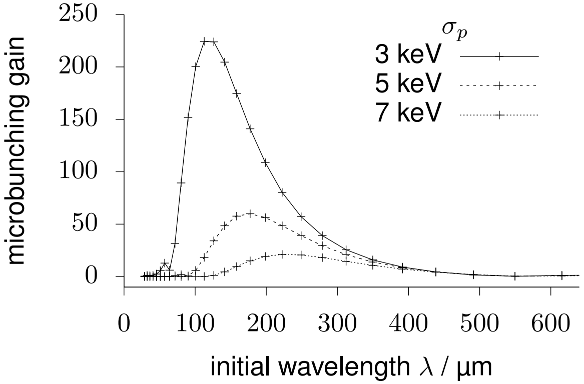
As for the amplification mechanism itself, an effective way to suppress the gain is to increase local energy spread since the gain critically depends on this parameter. For instance, increase of the energy spread at TTF2 up to 15-20 keV would eliminate the instability.

[...]

method does not work because of the relatively low energy. A simple method to control the energy spread at low energy would be to use FEL type modulation of the beam in optical wavelength range by a laser pulse in an undulator. Then the beam goes through the bunch compressor where these coherent energy modulations are quickly dissipated, leading to the effective "heating" of the beam [4]. For illustration we present here a nu-

Simulations for FLASH2020+:

$I_0 = 31$ A, $C = 4 \times 4$ (seeding)



Theory:

$$\frac{\text{linear gain}}{\text{stage}}\Big|_\lambda (\sigma_p) \propto \exp\left(-\pi\, C\, \frac{M_{56}}{\lambda}\, \frac{\sigma_p}{E_0}\right)$$

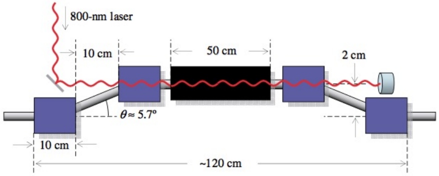
Laser Heaters around the World.

LCLS (2010)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 020703 (2010)

Measurements of the linac coherent light source laser heater and its impact on the x-ray free-electron laser performance

Z. Huang, A. Brachmann, F.-J. Decker, Y. Ding, D. Dowell, P. Emma, J. Frisch, S. Gilevich, G. Hays, Ph. Hering, R. Iverson, H. Loos, A. Miahnahri, H.-D. Nuhn, D. Ratner, G. Stupakov, J. Turner, J. Welch, W. White, J. Wu, and D. Xiang
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 4 December 2009; published 17 February 2010)



FERMI@Elettra (2014)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 17, 120705 (2014)

Laser heater commissioning at an externally seeded free-electron laser

S. Spampinati,[1,2,*] E. Allaria,[1] L. Badano,[1] S. Bassanese,[1] S. Biedron,[1,∥] D. Castronovo,[1] P. Craievich,[1,†] M. B. Danailov,[1] A. Demidovich,[1] G. De Ninno,[1,2] S. Di Mitri,[1] B. Diviacco,[1] M. Dal Forno,[1,3,‡] E. Ferrari,[1,3] W. M. Fawley,[1] L. Fröhlich,[1,§] G. Gaio,[1] L. Giannessi,[1,4] G. Penco,[1] C. Serpico,[1] C. Spezzani,[1,¶] M. Trovò,[1] M. Veronese,[1] S. V. Milton,[1,∥] and M. Svandrlik[1]
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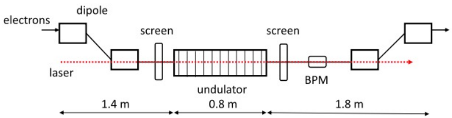
[4]*Theory Group–ENEA C.R. Frascati, 00044 Frascati (Rome), Italy*
(Received 27 September 2014; published 18 December 2014)

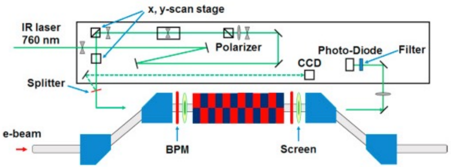


PAL-XFEL (2017)

Nuclear Instruments and Methods in Physics Research A 843 (2017) 39–45

PAL-XFEL laser heater commissioning

JaeHyun Lee[a], Jang-Hui Han[b,*], Sojeong Lee[b], Juho Hong[b], Chul Hoon Kim[b,1], Chang Ki Min[b], In Soo Ko[a,b]
[a] *Department of Physics, POSTECH, Pohang 37673, South Korea*
[b] *Pohang Accelerator Laboratory (PAL), Pohang 37673, South Korea*



European XFEL (2016)

WEPG32 Proceedings of IBIC2016, Barcelona, Spain

FIRST HEATING WITH THE EUROPEAN XFEL LASER HEATER*

M. Hamberg[†], Uppsala University, Uppsala, Sweden,
F. Brinker, M.Scholz, DESY, Hamburg, Germany

Typical Laser Heater Layout:

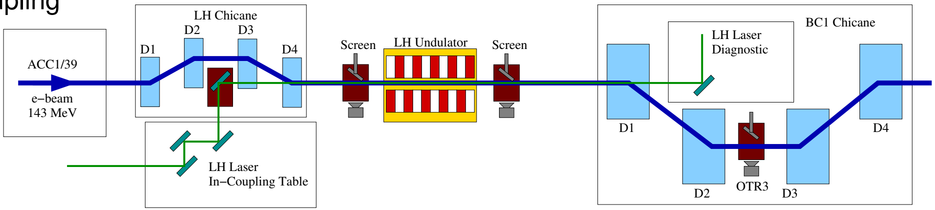
- LH undulator in small chicane
  ↪easy in/out-coupling of the LH laser
- Modulations are fold-over by M_{56} of the half-chicane
  ↪small M_{56} potentially causes trickle heating (LCSL 2010)

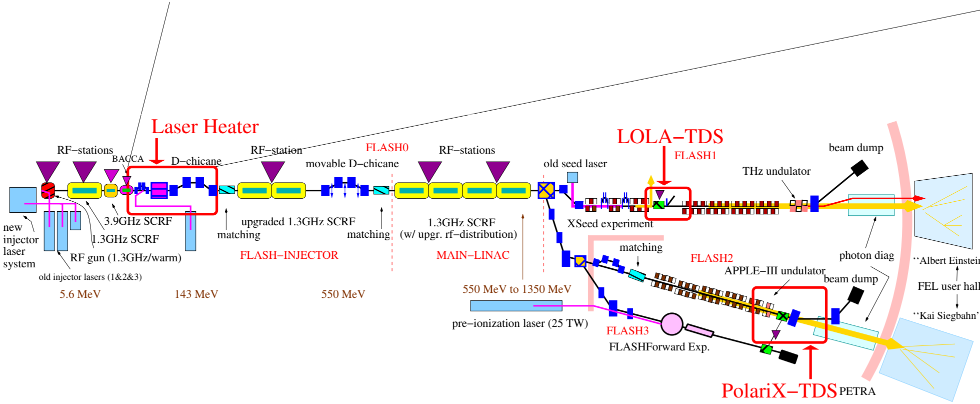
FLASH2020+ Laser Heater Layout.

- LH undulator in non-dispersive, straight section
  →avoids beam tilts due to energy chirp from ACC1/39
  →requires in-vacuum mirror for laser incoupling
  ↪incoupling chicane needed
- Short LH laser wavelength: 532 nm
  →shorter energy-modulation wavelength
  ↪more effective over-folding
  →dedicated LH laser system required
- LH Undulator

E_0	143 MeV
λ_L	532 nm
periods	11
λ_U	43 mm
min. gap	22 mm
K	1.42

- Two TDS's for Long. Phase-Space Diag.
  →FLASH1: "LOLA"
  →FLASH2: "PolariX"





Shutdown 2021/2022: Installation of LH section & LH laser beamline.

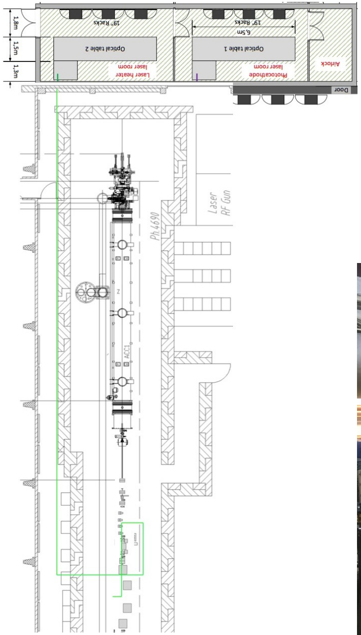
Old BC2
pre-shutdown

Beamline components
removed

Supports
removed

Installation of
new LH section

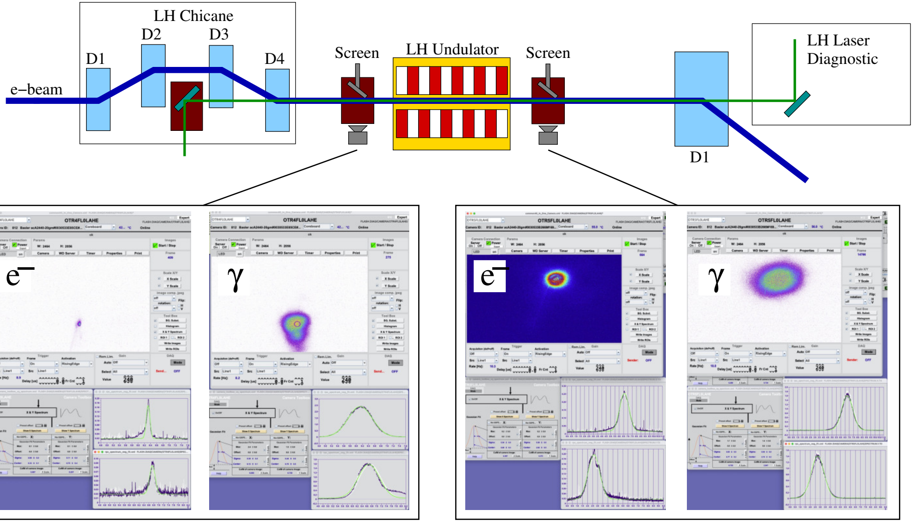
LH Laser Beamline.



- LH laser system
  →Yb:fiber / Nd:YVO4 laser system
  →frequency-doubled to $532\,\mathrm{nm}$
  →low-bandwidth
- LH laser beamline
  →$\approx 30\,\mathrm{m}$
  →relay-imaging w/ 2 lenses, 6 mirrors

Spatial Overlap.

- Chromox Screens
  up-/down-stream of LH undulator
- Overlap cannot be established
  in parallel to operation
- To be commissioned:
  →LH laser position feedback
  →beam expander for
  spot-size control
- Typically:
  → $\sigma_{e^-} \approx 100\,\mu m$
  → $\sigma_L \approx 600\,\mu m$

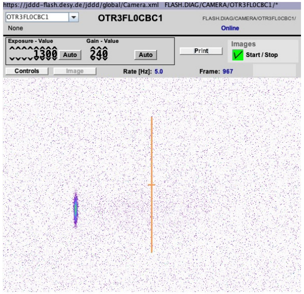


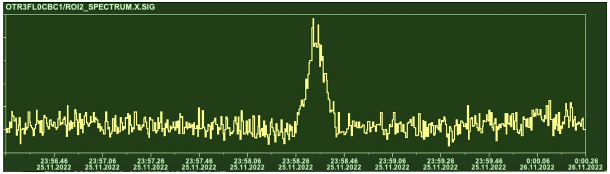
"Impressions from the control room . . . "

Temporal Overlap.

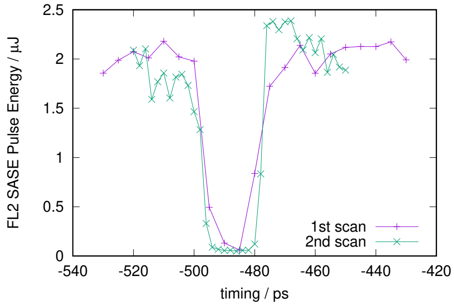
- Coarse Timing: Laser & LH-Undulator Radiation on Photo-Diode: ~ 1 ns

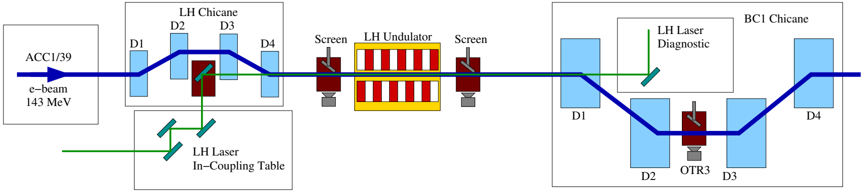
- Fine Timing Option #1:
  →Signal: energy spread via beamsize on screen in compression chicane
  →Minimize “unheated” beamsize via RF-settings & Optics
  →First Heat on 2022-11-25
  →disrupts operation



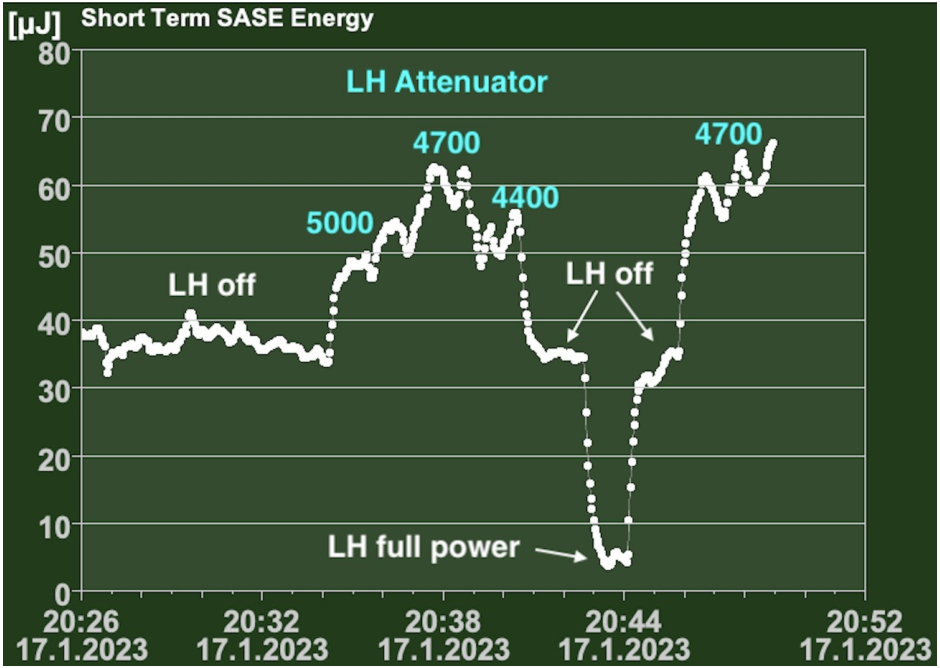


- Fine Timing Option #2:
  →Signal: SASE Suppression
  →compatible w/ nominal machine setup

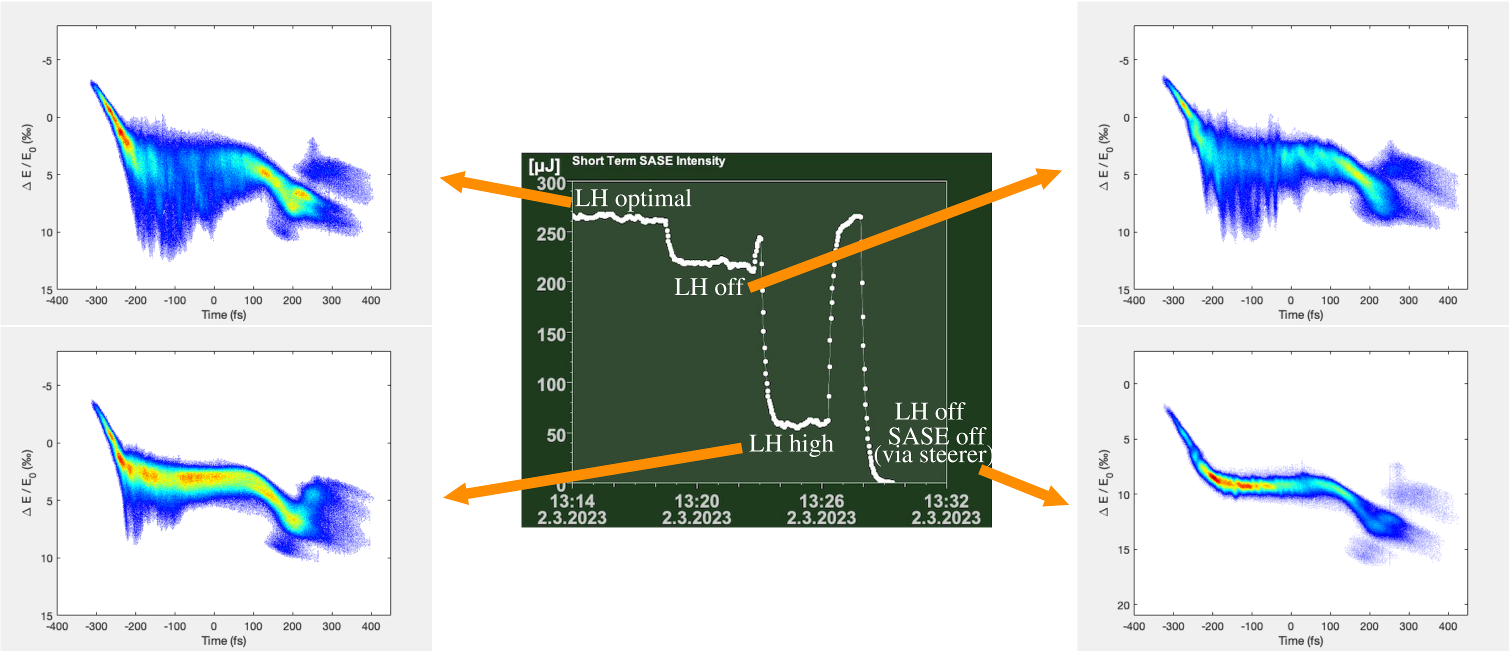




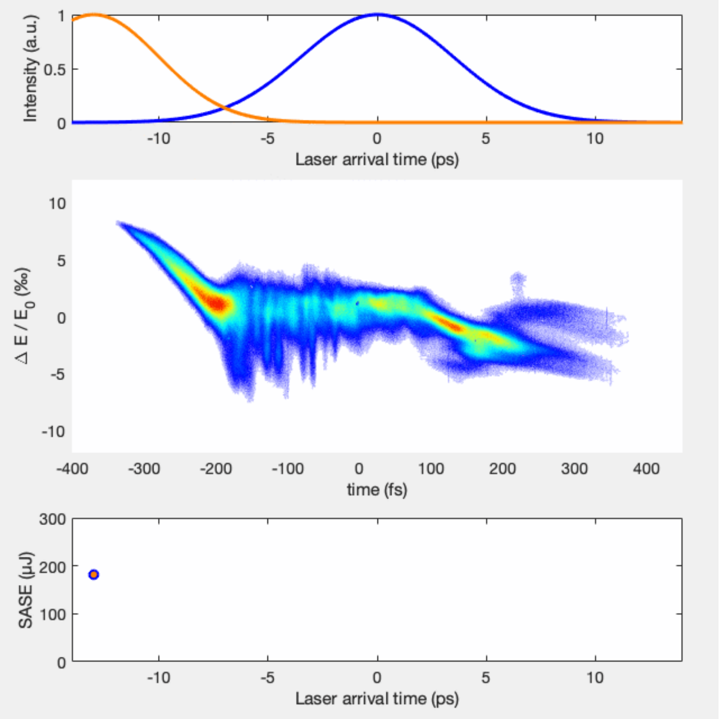
Evidence of SASE Enhancement by LH.



LH Effect on SASE Process in FLASH2 (PolariX-TDS).



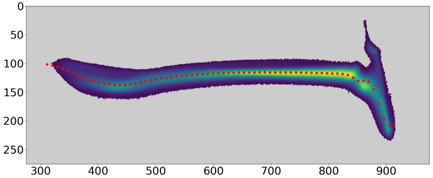
LH Laser Timing Scan.



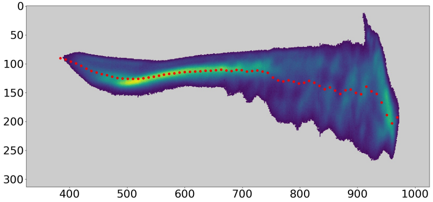
PolariX: Photon Pulse Length.

(Ch.Behrens)

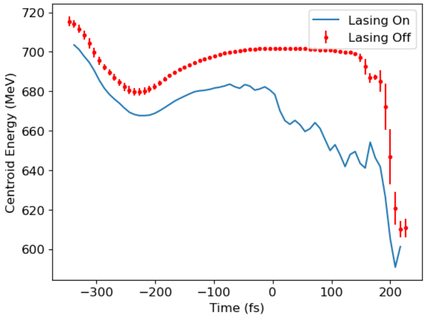
SASE suppressed (via steerer)



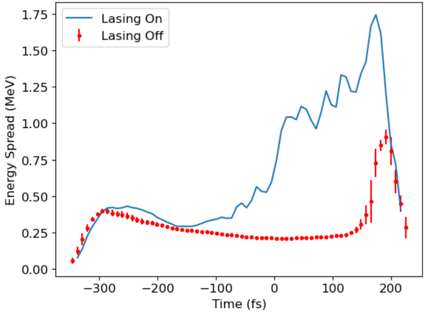
SASE optimized



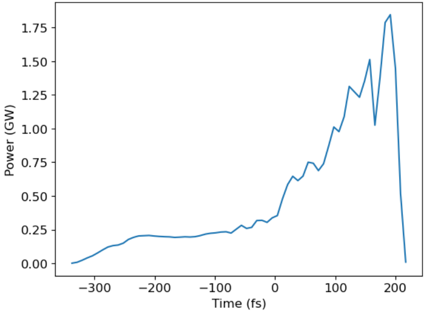
Local Mean Energy



Local Energy Spread



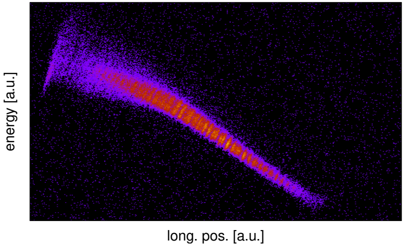
Photon Pulse Profile



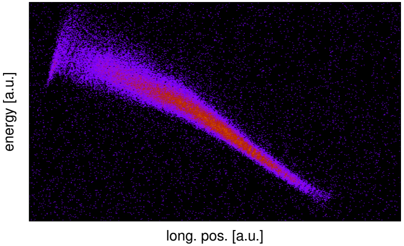
Microbunching Studies in FLASH1/FLASH2.

FLASH1 (LOLA-TDS) BC1 →BC2 →Dogleg

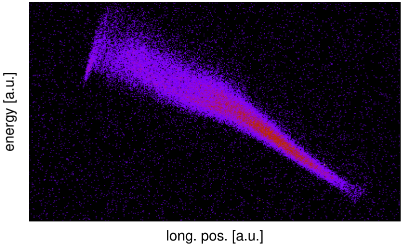
LH off



LH medium

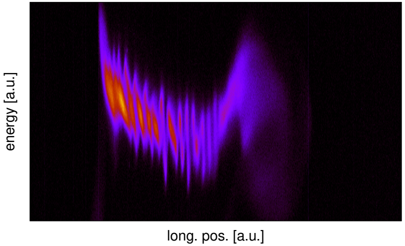


LH maximum

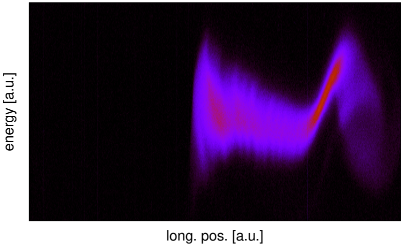


FLASH2 (PolariX-TDS) BC1 →BC2 →Extraction →FL2BC

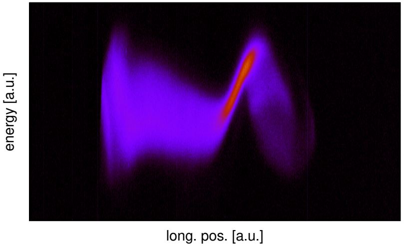
LH off



LH medium



LH maximum



MBI Image Analysis Challenge.

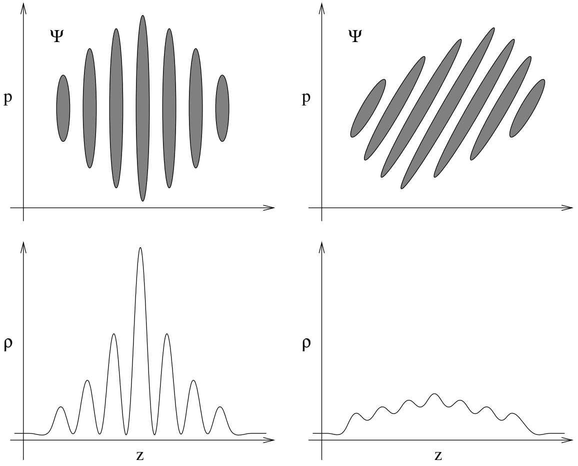
Naive approach:

- Obtain charge density by projecting along p-axis:

$$\rho(z) = \int_{\mathbb{R}} \Psi(z,p)\mathrm{d}p$$

- Analyse Fourier components:

$$\tilde{\rho}(k) = \mathcal{F}_{k\leftarrow z}\rho(z) = \iint_{\mathbb{R}^2} \Psi(z,p)\exp(-ikq)\mathrm{d}z\mathrm{d}p$$



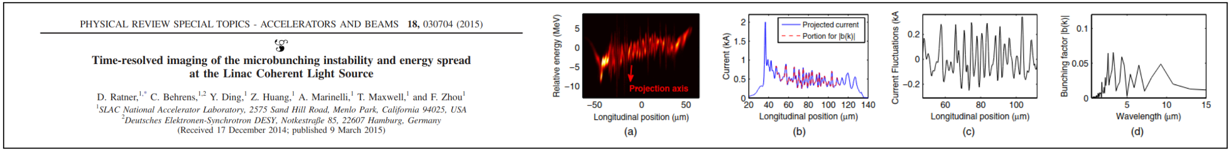
Problem:

- Tilted microbunches overlap
- Modulations in charge density “smear out”
  $\implies$ reduced amplitude & contrast
- Impact of microbunching will be underestimated
  (if even resolvable)

$\Rightarrow$**Tilt has to be taken into account!**

MBI Image Analysis Methods.

- Ratner 2015: Project along *fixed, predetermined* angle


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18**, 030704 (2015)

Time-resolved imaging of the microbunching instability and energy spread at the Linac Coherent Light Source

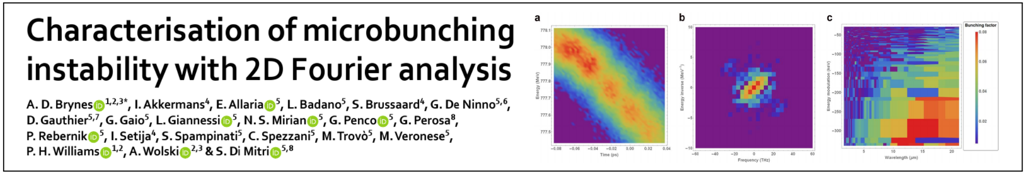
D. Ratner,[1,*] C. Behrens,[1,2] Y. Ding,[1] Z. Huang,[1] A. Marinelli,[1] T. Maxwell,[1] and F. Zhou[1]

[1]*SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA*

[2]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany*

(Received 17 December 2014; published 9 March 2015)

- Brynes 2020: *2D-Fourier* Transform, zoom-in on "satellites"


Characterisation of microbunching instability with 2D Fourier analysis

A. D. Brynes[1,2,3*], I. Akkermans[4], E. Allaria[5], L. Badano[5], S. Brussaard[4], G. De Ninno[5,6], D. Gauthier[5,7], G. Gaio[5], L. Giannessi[5], N. S. Mirian[5], G. Penco[5], G. Perosa[8], P. Rebernik[5], I. Setija[4], S. Spampinati[5], C. Spezzani[5], M. Trovò[5], M. Veronese[5], P. H. Williams[1,2], A. Wolski[2,3] & S. Di Mitri[5,8]

- *Today*: Radon-Transform Method

The Radon-Transform.

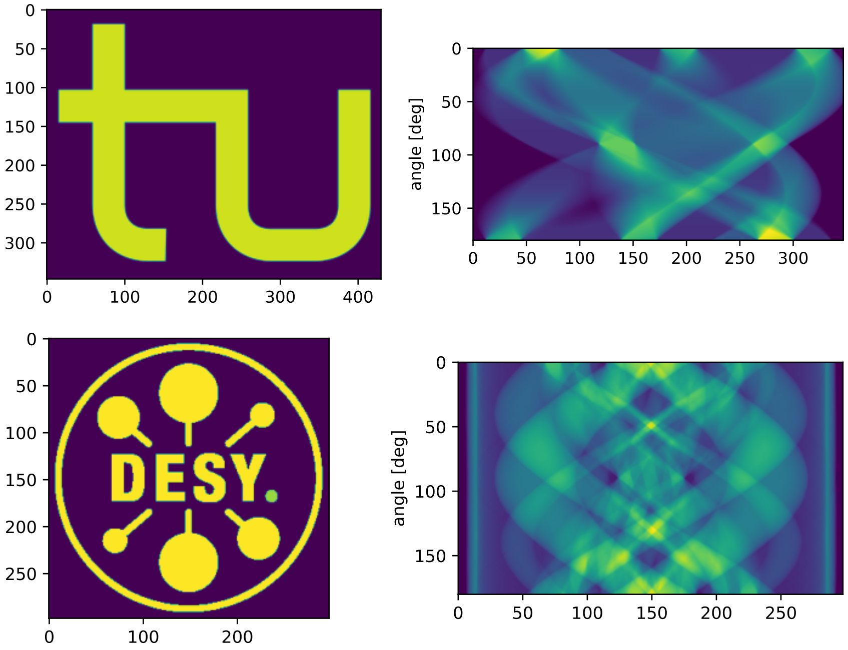
- Tansforms from cartesian space to “angle/displacement”–space

$$f(x,y) \mapsto \mathcal{R}f(x,\alpha) \equiv \int_{\mathbb{R}} [f \circ R(-\alpha)](x,y)\,\mathrm{d}y$$

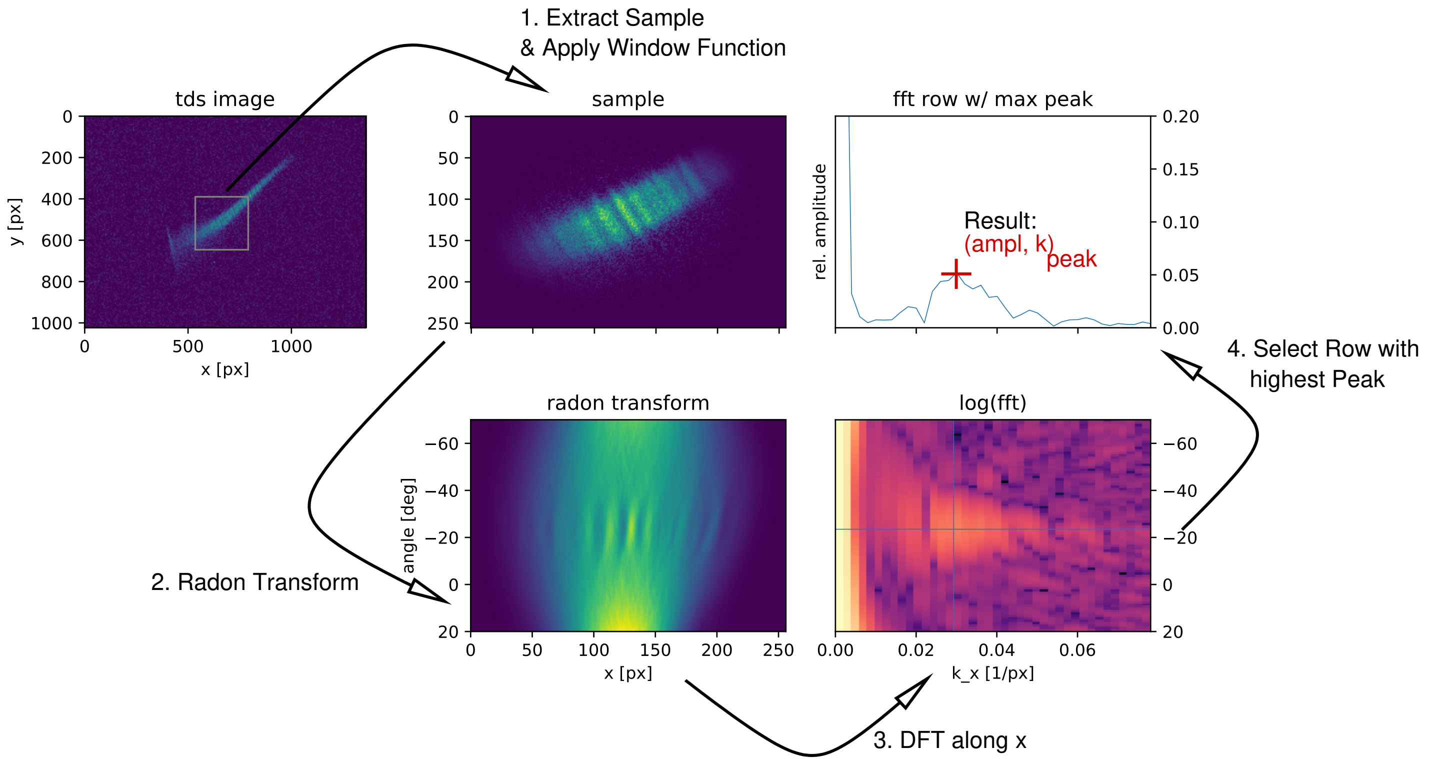
where

$$R(\alpha) : \begin{pmatrix} x \\ y \end{pmatrix} \mapsto \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

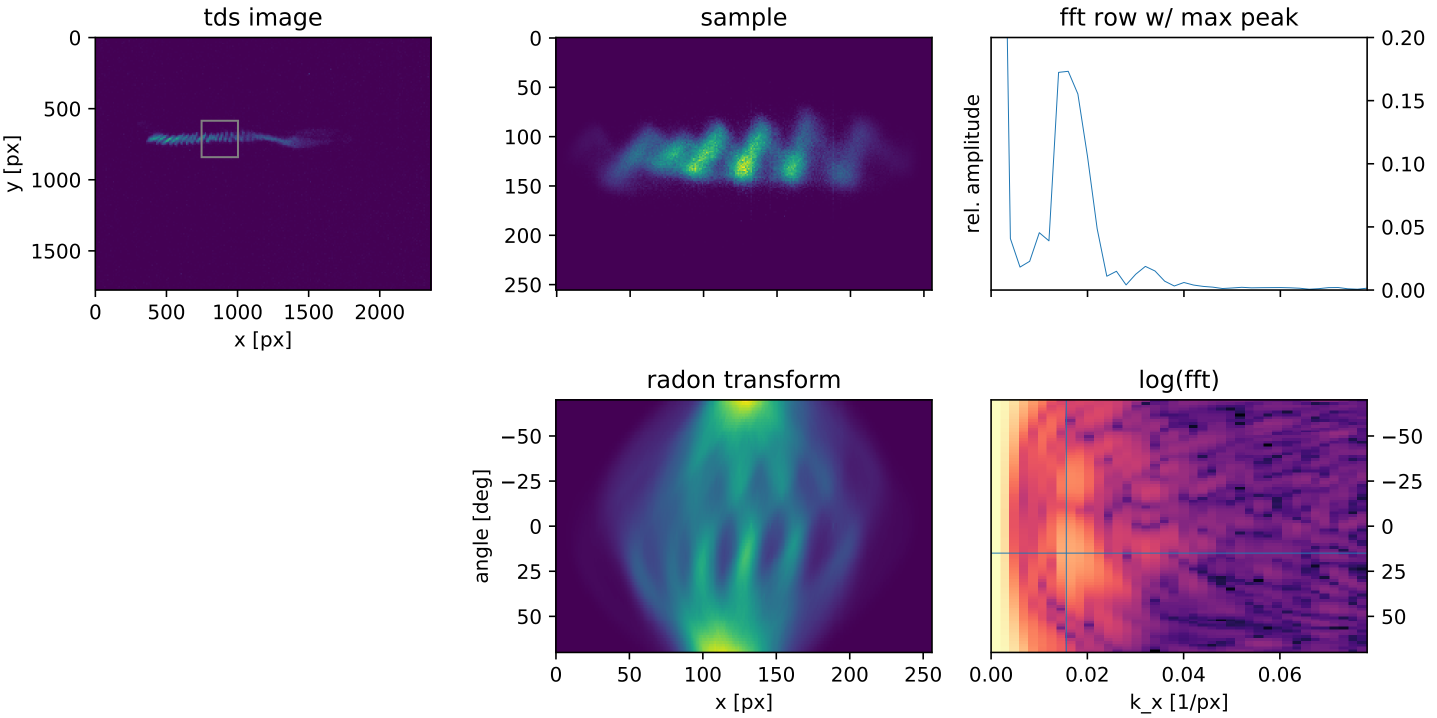
- Rotation angle α becomes new independent variable



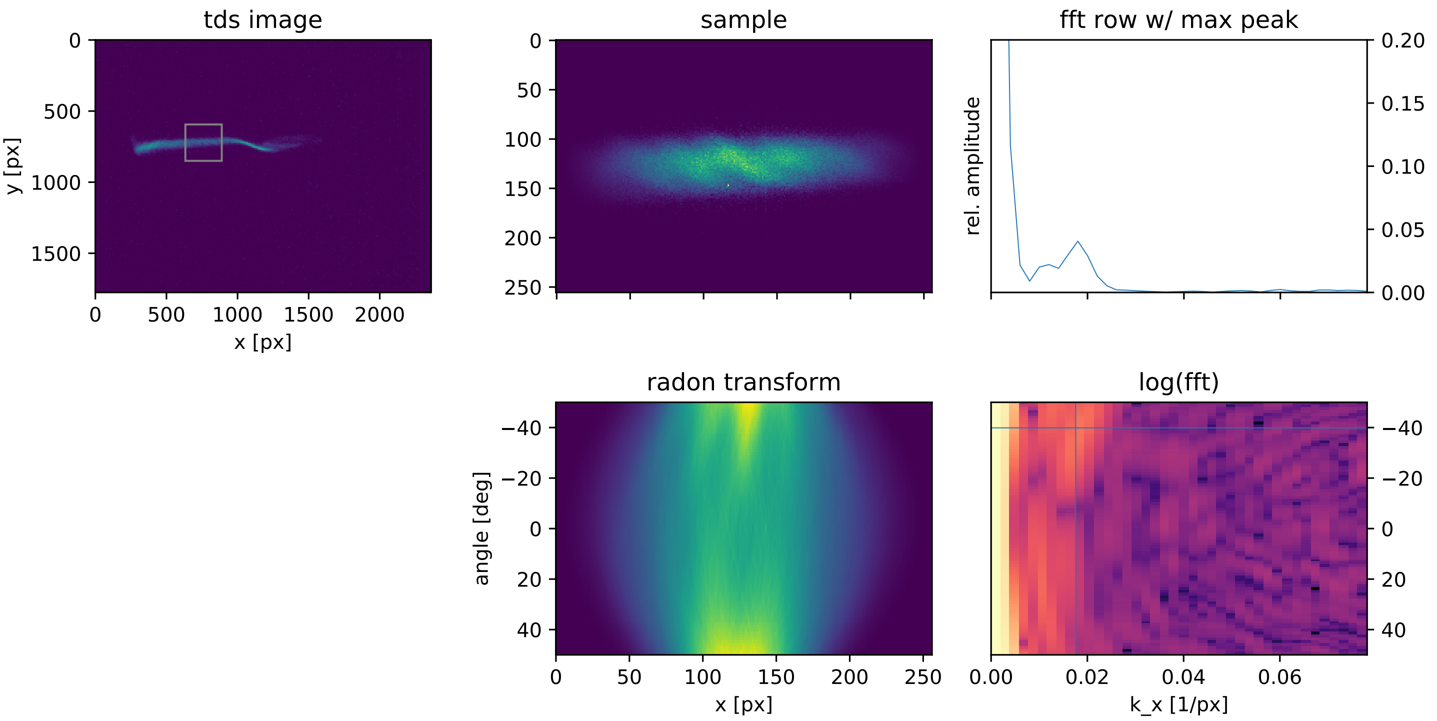
Principle: Radon-Transform based MBI Analysis.



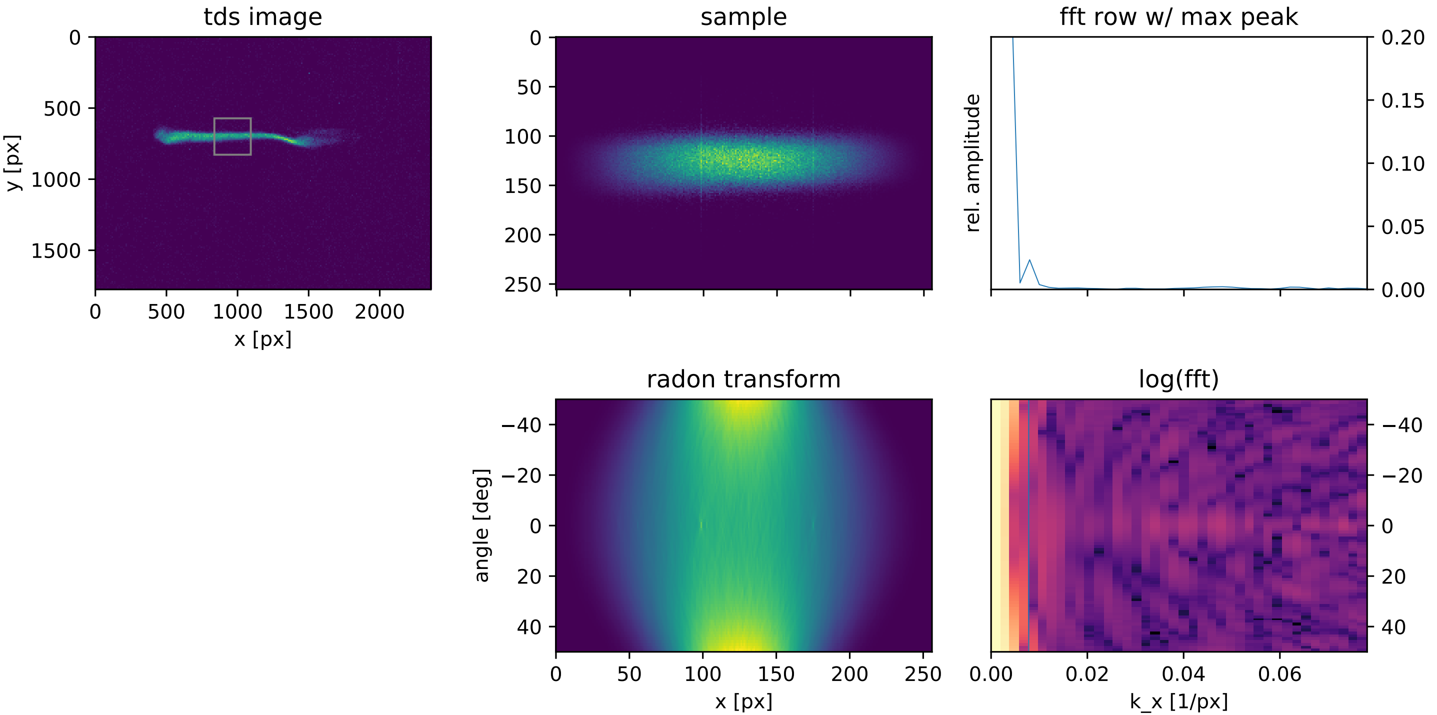
Example: FLASH2 (PolariX-TDS) – strong uB.



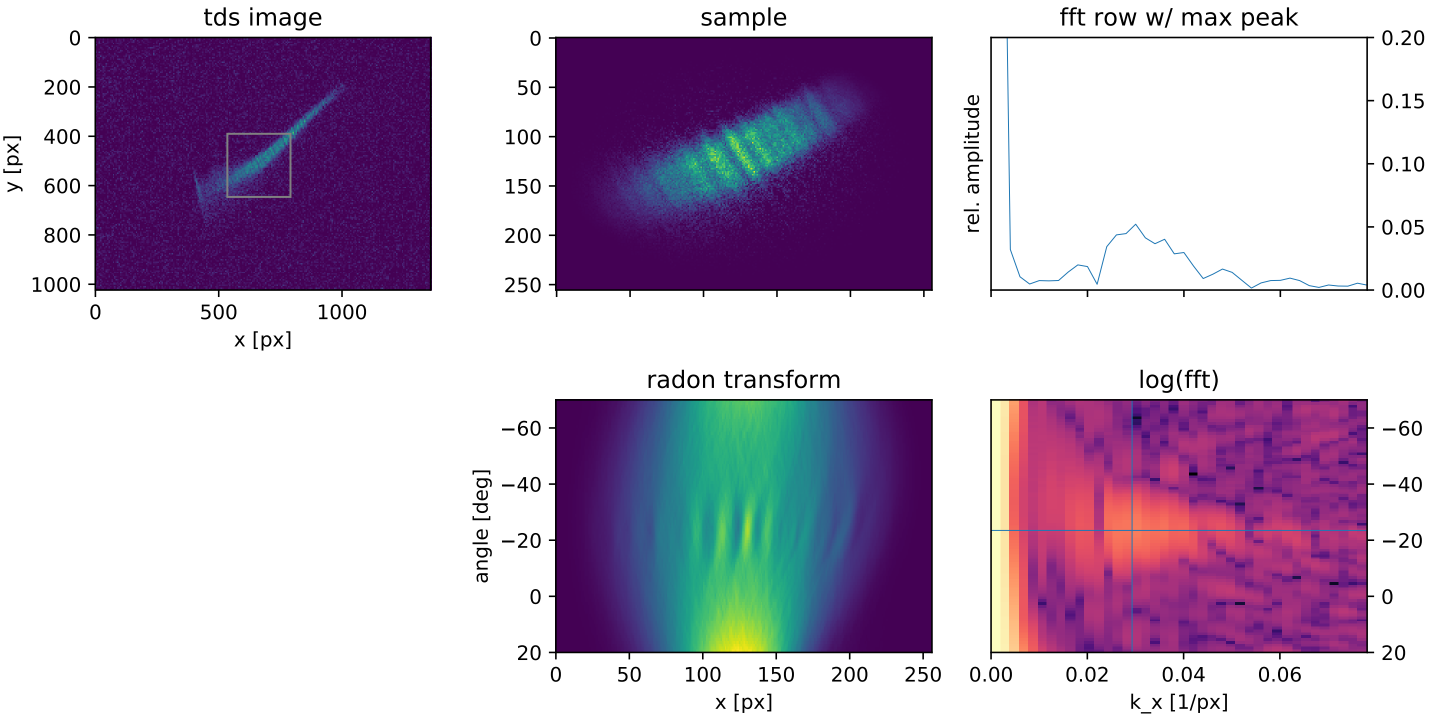
Example: FLASH2 (PolariX-TDS) – intermediate uB.



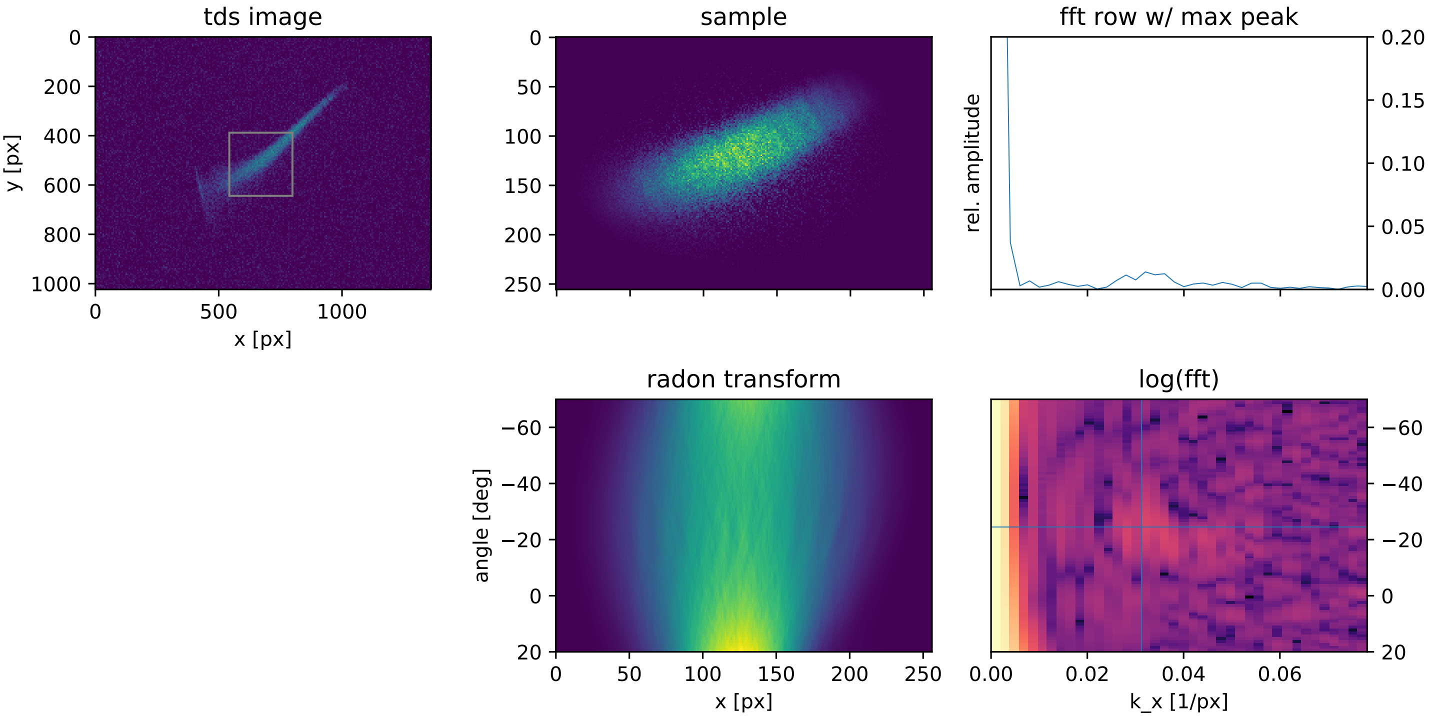
Example: FLASH2 (PolariX-TDS) – no uB.



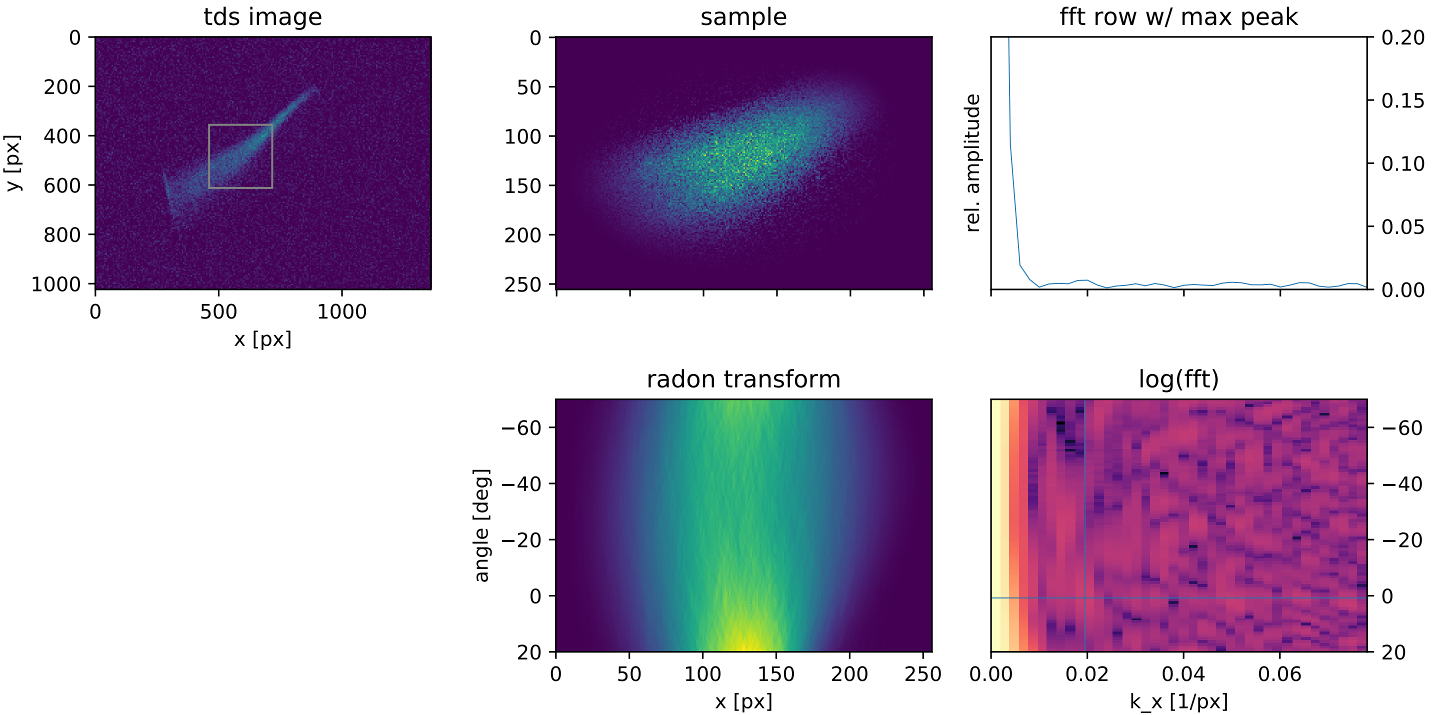
Example: FLASH1 (LOLA-TDS) – strong uB.



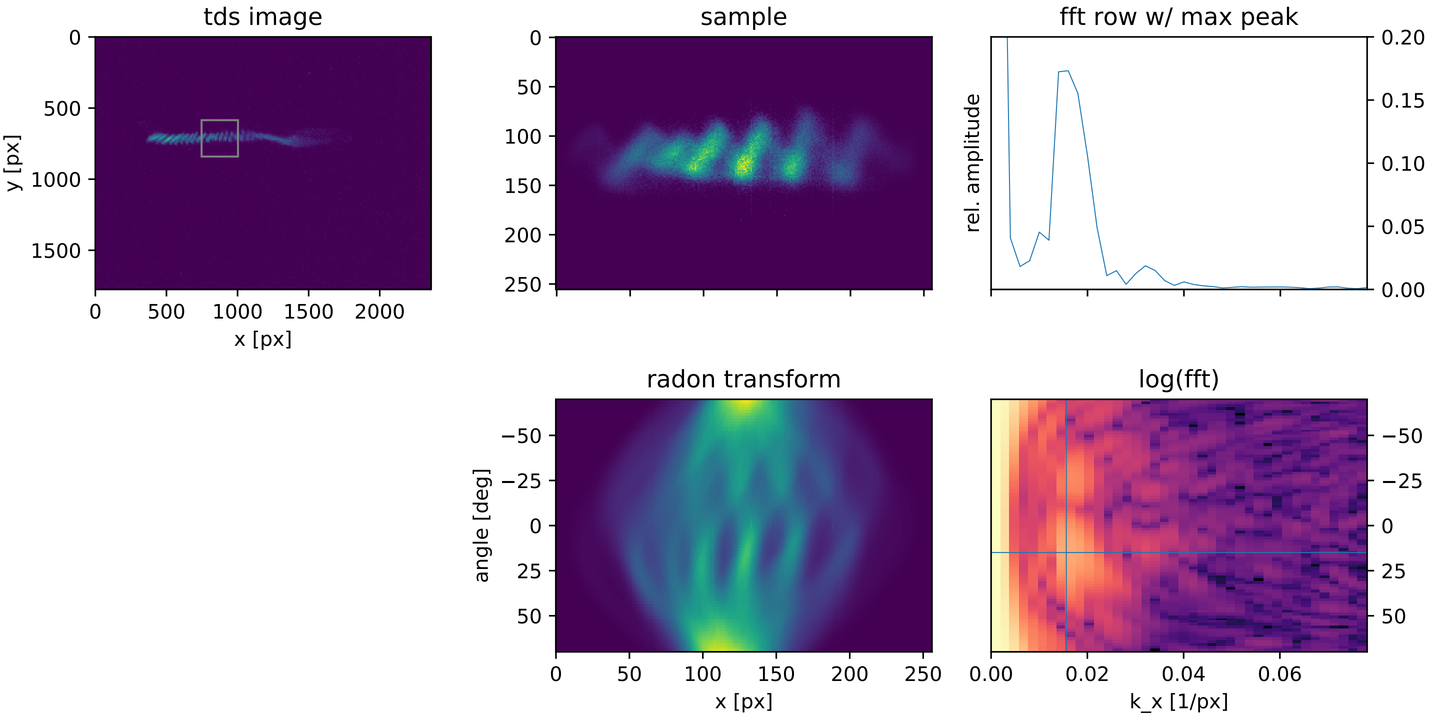
Example: FLASH1 (LOLA-TDS) – intermediate uB.



Example: FLASH1 (LOLA-TDS) – no uB.



Example: PolariX.



Comparison with other Methods.

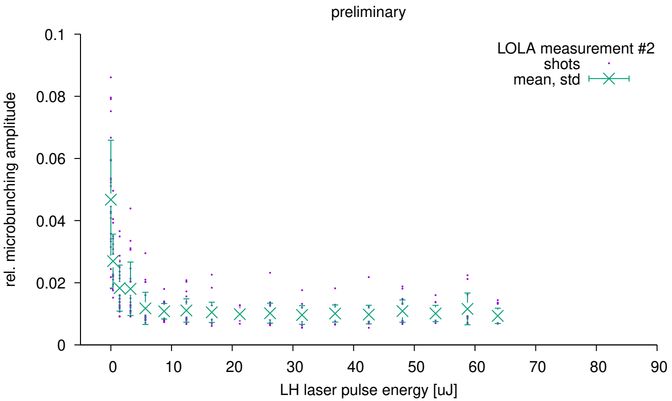
- Radon-Method is closely related to *both* Ratner'15 and Brynes'20
  - $\rightarrow$ Ratner'15 chooses α ab initio $\leftrightarrow$ we "scan" α and take the optimum
  - $\rightarrow$ Brynes'20 analyses FFT in (k_z, k_E)-space $\leftrightarrow$ we look at FFT in (k, α)-space
    - $\hookrightarrow$ (k_z, k_E)-representation can be constructed from (k, α)-repr. by "unrolling" the slices
    - $\hookrightarrow$ Radon-method seems to provide better "angular" resolution

- Image analysis in "Radon-space" likely allows further refinements:
  - $\rightarrow$ symmetry analysis
  - $\rightarrow$ 2D-peak-finding (taking into account adjacent angles)
  - $\rightarrow$ work in progress . . .

Microbunching Suppression Results.

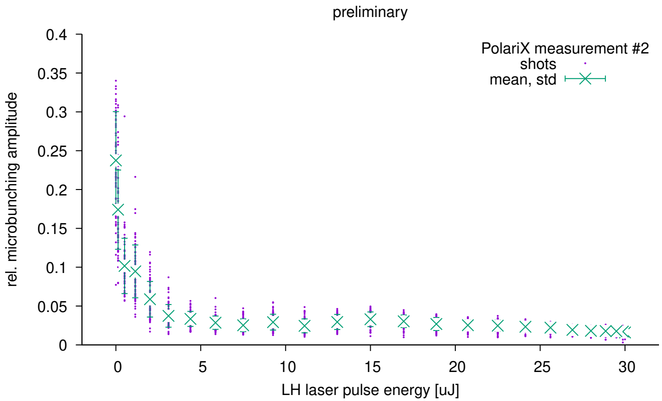
(preliminary)

FLASH1 (TDS: “LOLA”)



- Full suppression: $E_{\mathrm{LH}} \gtrsim 10\,\mu\mathrm{J}$
- Longitudinally Dispersive Elements:
  ↪BC1 →BC2 →Dogleg

FLASH2 (TDS: “PolariX”)



- Full suppression: $E_{\mathrm{LH}} \gtrsim 8\,\mu\mathrm{J}$
- Longitudinally Dispersive Elements:
  ↪BC1 →BC2 →Extraction →FL2BC

Possible Figure of Merit to compare w/ Theory.

(preliminary)

- For fixed compression, charge, initial conditions, optics, etc. the uB-gain G at some *fixed* frequency depends on the energy-spread via

$$G \propto \exp(-\kappa\, \sigma_E^2)$$

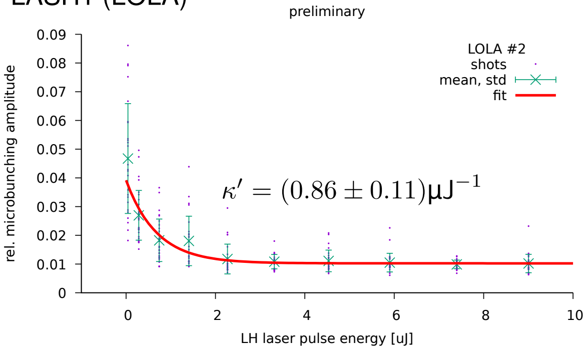
(assuming a Gaussion energy distribution)

- κ can be determined from first-order perturbation theory

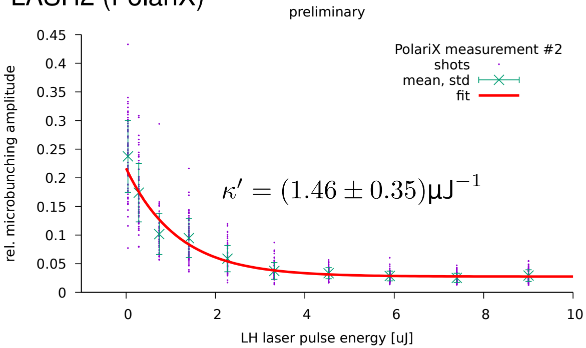
- Assume heating increases energy spread via: $\sigma_E^2 \mapsto \sigma_E^2 + \Delta\sigma^2$ and $\Delta\sigma \propto \sqrt{E_{\mathrm{LH}}}$

$$\implies G \propto \exp(-\kappa'\, E_{\mathrm{LH}})$$

FLASH1 (LOLA)



FLASH2 (PolariX)

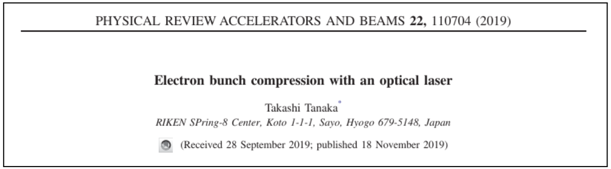


FLARE Project.

- **F**LASH **L**aser-**A**ssisted
  Reshaping of **E**lectron Bunches

- BMBF funded project (C.Mai, TU Dortmund)

- Principle proposed in 2019 by T.Tanaka



PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 110704 (2019)

Electron bunch compression with an optical laser

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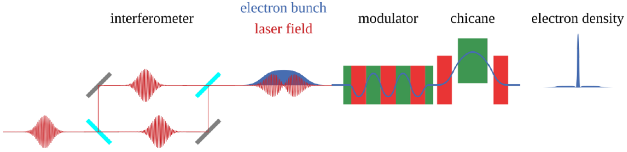
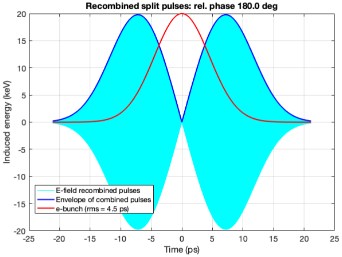
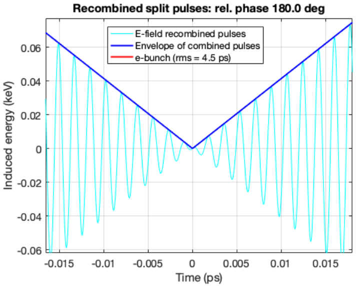
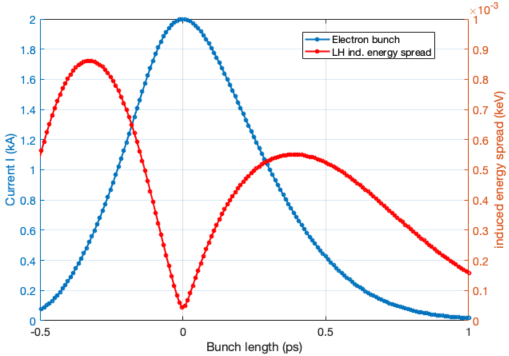






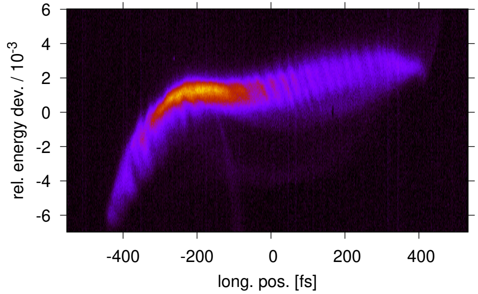


- Split-and-Delay the LH Laser Pulse
  →no heating in the center
  →nearly linear envelope flanks in the center
  ↪compression!

FLARE: First Signs of LH-Pulse Interference.

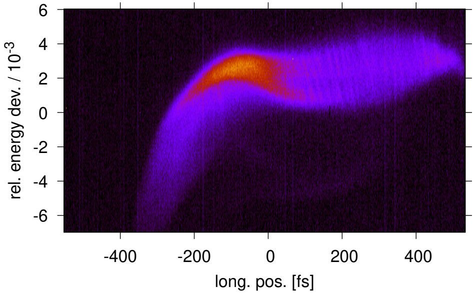
(most preliminary, last week's results)

No LH Pulses



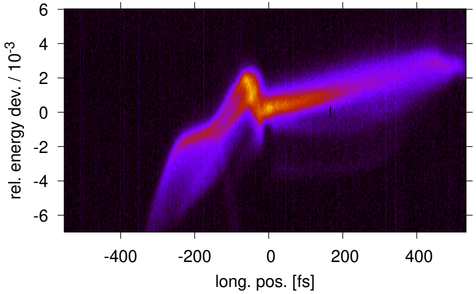
- No SASE
- Long Bunch

Single LH Pulse



- MBI suppressed in half of the bunch (left)

Both LH Pulses



- MBI suppressed in the whole bunch
- Interference generates “blip” in LPS $\rightarrow$most likely space-charge assisted

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- Interference of split-and-delayed LH laser pulses
- First signs of current spike formation
- Optimization of machine setup required (compression settings) $\rightarrow$simulations are under way

Work in progress!

Thank you for your attention.

Backup.

Gap Scan & Induced Energy Spread.

- LH Undulator gap setting

$$\lambda(g_u) = \frac{\lambda_u}{2\gamma_0^2}\left[1 + \frac{K(g_u)^2}{2}\right] \overset{!}{=} 532\,\text{nm}$$

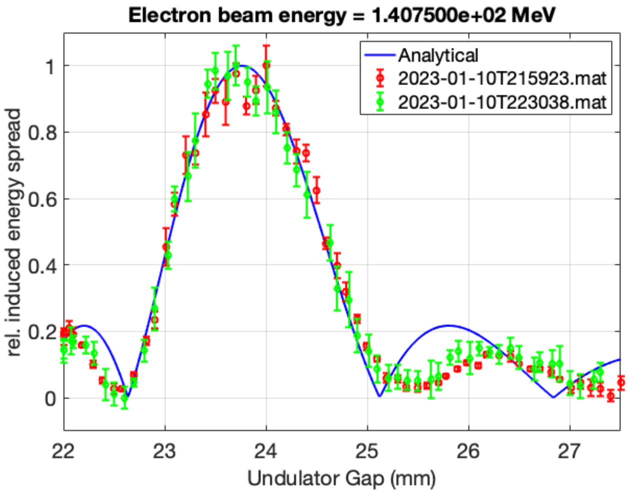
- Induced Energy Spread

$$\sigma_{\Delta E}(g_u) = \sigma_{\Delta E,\max}\,|\text{sinc}\,(\pi\,N_u\,\delta_\lambda)|$$

with

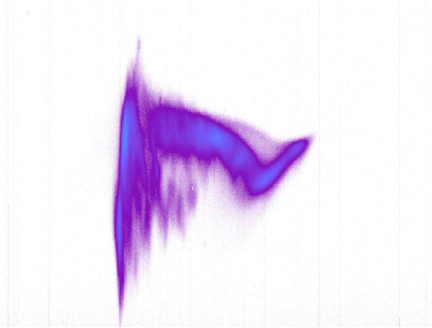
$$\delta_\lambda \equiv \frac{\lambda(g_u) - \lambda_L}{\lambda_L}$$

- Gaussian Fit to Horizontal beam size at screen in BC1
  $\rightarrow$analytical equation: $140.7\,\text{MeV}$
  $\rightarrow$measured e-beam energy: $143\,\text{MeV}$

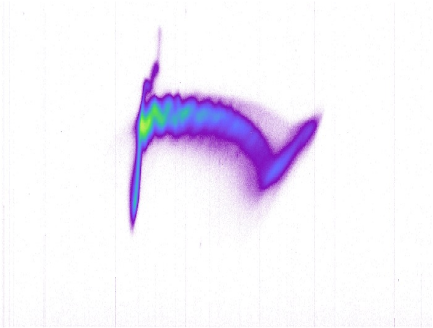


PolariX: SASE Machine Learning Data.

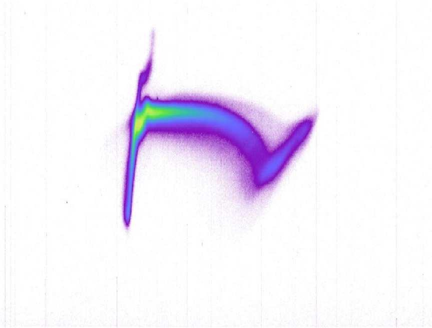
SASE Optimized
↪ $\sim 250\,\mu J$
LH Optimized



SASE Suppressed
↪(via steerer)
LH off



SASE Suppressed
↪(via steerer)
LH Optimized



SASE Suppressed
↪(via steerer)
LH maximum power